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Massachusetts Institute of Technology

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Submitted in Partial Fulfillment of the Requirements for the Master of Science Degree in Aeronautical Engineering from the Massachusetts Institute of Technology

1947

Cambridge, Massachusetts
23 May 1947

Professor Joseph S. Newell
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Professor Newell:

A thesis entitled "The Effect of Residual Gas Concentration and Engine Speed on the Detonation Characteristics of Iso-Octane, Di-iso-butylene, Triptane and Ethyl Benzene" is herewith submitted in partial fulfillment of the requirements for the degree of Master of Science in Aeronautical Engineering.

Respectufl1y yours,

Cambridge, Massachusetts
25 May 1967

Professor Ralph J. Hooli
Secretary of the Faculty
Massachusetts Institute of Technology
Cambridge, Massachusetts

Dear Professor Hooli:

I hereby nominate "The Times of Thelonk Sha
Characteristics and Logics Used in the Operation
Characteristics of Geo-Ocean, Air-Air-Fighter, Fighter
and Light Cannon" in Juvenile Animated In Period
Fulfillment of the requirements for the Degree of Master
of Science in Internal Exploration.

Respectfully yours,

Robert L. Greene, Jr. Grad. Dept.

William M. Hall, Jr. Chair. Dept.

John C. Green, Jr. Chair. Dept.

Robert Berry, Elec. Dept.

ACKNOWLEDGMENT

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Professor W. A. Leary, M.I.T. Staff
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Instructor C. H. Kano, M.I.T. Staff
and
the mechanics and assistants of the Sloan Laboratory.

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INTRODUCTION

The purpose of this paper is to study the effect of residual gas concentration on the critical pressure-time characteristics of (1) Iso-Octane, (2) Di-iso-butylene, (3) Triptane, and (4) Ethyl Benzene.

It has been observed by experimenters in the General Motors Laboratory, Sloan Laboratory, and elsewhere, that the critical pressure of Iso-Octane increases with increase in RPM while the critical pressures of Ethyl Benzene, Triptane, and Di-iso-butylene decrease with increase in RPM. The simple auto ignition theory does not account for this behavior since it states that the critical pressure should increase with increase in RPM regardless of the fuel, provided other variables are held constant.

A further study of the subject by Leary and Taylor (Reference 1) showed that the effect of engine speed on critical pressure is due to "time effect" alone. The expression "time effect" is defined as

(1) the rate at which the end gas is compressed and

(2) the time required by the end gas to complete the necessary preliminaries to explosion.

The term "critical pressure" is defined as

(1) that pressure at which the end gas explodes to cause the phenomenon known as detonation.

It is suspected that the residual gas concentration in the end gas may influence the "time effect" in such a way as to cause an increase in critical pressure with increased RPM using Iso-Octane, and a decrease in critical pressure with increased RPM using Ethyl Benzene, Triptane, and Di-iso-butylene.

It is suggested that the individual who concentrates in
his oral can make any inference the "time allows" in such a way as
to cause an instructor to criticize primarily with increased con-
viction. Two-question, and a discussion in oriented professors with
increased self-testing daily lessons, rhetoric, and discus-
sions.

SUMMARY

It was found that the critical pressure of Triptane, Ethyl Benzene and Di-iso-butylene was higher at 900 RPM than at 1800 RPM at all values of residual gas concentration whereas the critical pressure of Iso-octane was higher at 1800 RPM than at 900 RPM for all values of residual gas concentration. Thus the residual gas concentration and its influence on time effects is not the cause of the difference in behavior of the detonation-RPM characteristics of Iso-octane from those of Triptane, Di-iso-butylene and Ethyl Benzene.

It was also found that at both RPM's an increase in residual gas concentration caused an increase in critical pressure for all fuels.

Summary

FUELS

The tests to be described were carried out on Iso-Octane, Di-iso-butylene (SR 10), Triptane and Ethyl Benzene. About twenty gallons of each of these fuels were required to complete the tests.

The Iso-Octane (2-2-4 trimethyl pentane) was obtained from Stanco Distributors, Inc. in five gallon drums. The calculated chemically correct fuel-air ratio was .0665.

The Di-iso-butylene was obtained from Stanco Distributors, Inc. under the designation SR 10 in five gallon drums. The calculated chemically correct fuel-air ratio was .0681.

The Triptane was obtained from N.A.C.A., Cleveland, Ohio, via the Bureau of Aeronautics, Navy Department. The chemically correct fuel-air ratio was .0662.

The Ethyl Benzene was obtained from the Dow Chemical Co. The chemically correct fuel-air ratio was .0736. Some difficulty was experienced in handling Ethyl Benzene because of its tendency to attack rubber and plastic and its nauceous odor.

DESCRIPTION OF APPARATUS

A standard C.F.R. single cylinder, water cooled, variable compression ratio engine 3.25 inch bore and 4.5 inch stroke having no valve overlap was used. (See Appendix B)

The air induction system consisted of an aluminum oxide drying tower (Reference 4) to keep the air humidity as low and as constant as possible, a surge tank, and a vaporizing tank, the temperature of which was controlled by any desired combination of steam and cold water. An immersion type electric heater, 220 volts, 4000 watts, was used to supplement the vaporizing tank when high inlet temperatures were used. The air supply came from a 100 lb/in.^{2} high pressure line and then came through high and low pressure regulator valves. After passing through the drying tower, the air was metered through a .515 inch A.S.M.E. orifice and the pressure differential across the orifice was measured with a standard water manometer.

The fuels were metered through a calibrated rotameter, Fisher and Porter, No. 1A-25, to a Bosch controllable flow injection pump which allowed any desired fuel rate to be set and held constant. The fuels were gravity fed with a head of approximately eight feet.

The exhaust system led through a surge tank in which cold water was sprayed for cooling purposes. The exhaust pressure

was controlled by means of a throttling valve and exhaust pump. A mercury manometer was used for measurement of normal exhaust pressure and a standard Bourdon tube gage was used for measuring high exhaust pressure.

Engine coolant temperature was held constant by allowing the jacket water to boil. Uniform cooling was aided by an externally driven centrifugal pump and excessive loss of water was prevented by a condenser coil at the top of the jacket.

The engine was connected to a D.C. dynamometer which was used as a motor for starting and as a generator for absorbing the power output of the engine when firing. To maintain the RPM at 900, two 60 ampere, 220 volt resistance stoves were used in the armature circuit. When operating at 1800 RPM, the armature discharged into the main line. The RPM could be accurately controlled by varying the dynamometer field strength and was measured by a tachometer and a strobotac operating on a 60 cycle frequency.

The ignition system operated from 110 volt D. C. line. The spark advance was controlled by a breaker mechanism coupled directly to the crankshaft. A Champion RJ-2 spark plug was used for Iso-Octane, Di-iso-butylene and Triptane. A Champion C-7 spark plug was used for Ethyl Benzene because of its tendency to foul the spark plug at low RPM.

Engine oil temperature was controlled by the proper regulation of steam or cold water in the oil heat exchanger.

tion of steam or cold water in the oil tank exchanger.

Engine oil temperature was controlled by the proper regulation of cooling water to the oil tank exchanger.

The spark advance was controlled by a breaker mechanism coupled directly to the crankshaft. A Champion UJ-6 spark plug was used for Iso-Octane, Di-Iso-Butylene and Xylene. A Champion U-7 spark plug was used for Ethyl Benzene because of its tendency to foul the spark plug at low RPM.

Engine oil temperature was controlled by the proper regulation of steam or cold water in the oil tank exchanger.

The engine was connected to a D.C. dynamometer which was used as a motor for starting and as a generator for absorbing the power output of the engine when firing. To maintain the RPM at 700, two 50 Ampere, 250 volt resistance stoves were used in the armature circuit. When operating at high rpm, the armature discharged into the main line. The RPM could be accurately maintained by varying the dynamometer field strength and was measured by a tachometer and a stroboscope operating on a 60 cycle frequency.

The ignition system employed four 14 volt D. C. Delco. Each spark advance was controlled by a breaker mechanism coupled directly to the crankshaft. A Champion UJ-6 spark plug was used for Iso-Octane, Di-Iso-Butylene and Xylene. A Champion U-7 spark plug was used for Ethyl Benzene because of its tendency to foul the spark plug at low RPM.

Engine oil temperature was controlled by the proper regulation of steam or cold water in the oil tank exchanger.

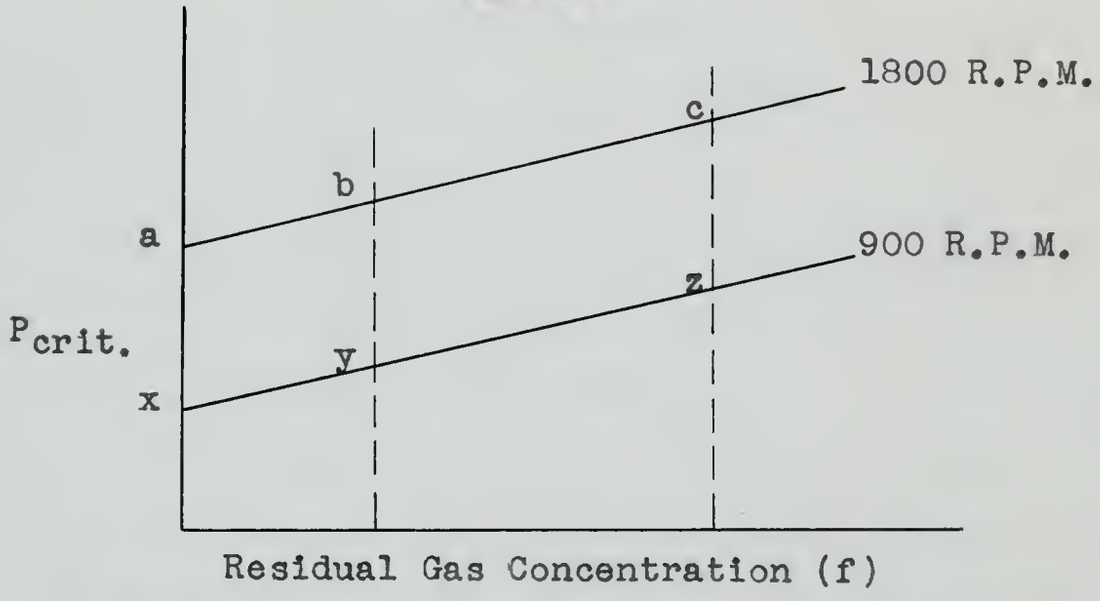
Incipient detonation was determined by a Dumont Oscillograph, type 168, using a M.I.T. magnetic pick-up whose output is proportional to dp/dt. (Reference 3) The engine indicator cards were taken on a M.I.T. high-speed engine indicator card machine using pressure balance springs giving 10, 20, 150 and 200 lbs. of pressure per inch of ordinate along with a M.I.T. balanced diaphram pick-up unit. (Reference 2)

PROCEDURE

Before a discussion of the actual experimental procedure can be attempted, it is necessary to look into the theory involved in order to justify some of the steps taken.

If the critical pressure is plotted against residual gas concentration (f), and the function is assumed to be linear, the result is a plot as shown in Figure A. The line a-b-c will then show the variation of critical pressure with residual gas concentration at 1800 RPM, and the line x-y-z will show the variation at 900 RPM. The fuel is assumed to be one which acts like iso-octane giving higher critical pressures at higher RPM's.

FIGURE A



Furthermore, it should be noted that at any point (z) on the 900 RPM line the same concentration of residual gas is in contact with the end gas for a longer time than at the

1800 R.P.M.
900 R.P.M.
C
B
Z
Y
X
Profit.
Residual Gas Concentration (f)

corresponding point (c) on the 1800 RPM line, the time of contact being inversely proportional to the RPM.

In order to compare the effect of residual gas concentration on the end gas at different RPM, a satisfactory basis of comparison had to be decided upon. If compression is assumed to be isentropic and two initial cylinder charges are chosen with identical fuel-air ratio, residual gas concentration, and initial entropy, both charges will follow the same compression path as plotted on a Pressure-Volume diagram or Temperature-Entropy diagram even though one charge is compressed at 900 RPM and the other at 1800 RPM.

By taking four such charges with identical initial entropy, two of which have a low residual gas concentration and two having a high residual gas concentration, the critical pressures may be measured and a plot may be constructed similar to Figure A. The absolute slopes of these plotted lines may then be explained on the basis of

(1) the residual gas concentration in the end gas, and

(2) the length of time in which the residual gas is in contact with the end gas.

In performing this experiment, two cylinder charges were chosen with the same initial entropy but with different residual gas concentration and the necessary data was obtained at 900 RPM to plot a line similar to x-y-z in Figure A. This was repeated at 1800 RPM attempting to maintain the same initial entropy and thereby plot a line similar to a-b-c. The actual experimental methods used are described below.

(3) the resistance and capacitance in the 2nd mesh, and

(4) the inputs at time t_0 when the readings are to be obtained

In performing this experiment, the following observations were carried out. Initial voltage for each different resistance and capacitance and the necessary data and obtained at 200 mV to give a time constant as shown in Figure 1. This was repeated at 1000 mV maintaining to maintain the same voltage constant and thereby give a time constant as shown.

EXPERIMENTAL PROCEDURE

Prior to firing, the engine was motored for several minutes by means of the dynamometer. Since the drying tower had to be reactivated after fourteen hours of use, atmospheric air was used during this and all other times that actual runs were not being made. At this time the top-dead-center line on the high speed indicator machine was checked and necessary adjustments were made if needed. The barometer was also read and calculated to an accuracy of one-hundredth of an inch of mercury. An approximate fuel-air ratio was set and when the temperature in the mixing tank reached a point where complete vaporization was assured, the ignition was turned on and the engine allowed to fire. After a warm-up period of about one hour, the RPM was adjusted to that desired.

In order to have a logical basis of comparison between runs made with the same fuel and same RPM but with different residual gas content, it was necessary to make some one point on the compression stroke of each of the two runs identical in cylinder pressure and specific volume, and consequently the same entropy. This point was arbitrarily taken at 110° of crank angle before top-dead-center as measured on the indicator card of the high-speed indicator machine. This point was chosen as close to the beginning of the compression stroke as possible consistent with good accuracy of pressure measurement on the indicator card.

It was decided to vary the residual gas content by means of the exhaust pressure. The two values of exhaust pressure used were 45 psia and 14.7 psia for high and low residual gas content respectively, with the exception of Ethyl Benzene. These pressures were obtained by means of a throttling valve placed in the pipe between the exhaust tank and the laboratory exhausting pump.

Since the high exhaust pressure was difficult to control, the first of each series of two runs was made with an exhaust pressure of 45 psia. The inlet temperature was held constant at a low value but high enough to give complete vaporization of fuel in the mixing tank. Inlet pressure was adjusted to give incipient detonation at a reasonable compression ratio.

With the RPM, exhaust pressure, inlet temperature and inlet pressure held constant, the air flow rate was measured and the corresponding fuel-air ratio was set by means of the rotameter and controllable flow fuel pump. The compression ratio giving incipient detonation was then obtained. Air flow rate was again measured, and, if a small deviation was noticed, the fuel rate was changed to keep a constant fuel-air ratio. The compression ratio was again checked, and, if a change was necessary, it was always so slight that no measurable difference was noticed in any of the other variables.

At this point all operating conditions were held constant, and pressure versus crank angle diagrams were made by means of

It was desired to test the material per formula 1p
series of five similar pressures. The two values of maximum
pressure used were 82 psig and 114.7 psig for high and low
residual gas content respectively, with the exception of
Proof Pressure. These pressures were obtained by means of
a Mercurially valve placed in the line between the cylinder
and the laboratory connecting rod.

Since the high exhaust pressure was difficult to
control, the first of each series of the runs was made with
an exhaust pressure of 82 psig. The light compression was
held constant at a low value but high enough to give sensitive
regulation of flow in the orifice tube. Data pressure was
obtained by the inclined manometer at a reasonable
convenient rate.

With the 1000, exhaust pressure, light compression and
light pressure held constant, the air flow rate was measured
and the corresponding flow-air ratio was run by means of the
tedious and controllable fine feed gear. The observation
rather during included temperature was also obtained. His flow
rate was again measured, and, if a small variation was noticed,
the feed rate was altered to keep a constant rate-air ratio.
The observations were made several, and, if a change was
necessary, it was simple to adjust that as necessary difference
was noticed in one of the other positions.

At this point all operating conditions were held constant,
and pressure rates were made directly by means of

the M.I.T. high-speed indicator card machine. These cards were used in the determination of residual gas content, critical pressure, and for maintaining similar cylinder conditions at 110° before top center for comparable runs. Depending upon the type of fuel used, with their accompanying cylinder pressures, cards were taken using springs giving either 10 lb/in. or 20 lb/in. ordinate for high accuracy at low pressures; and either a 150 lb/in. or 200 lb/in. ordinate spring was used for determining the critical pressure obtained in the cycle.

The cylinder pressure occuring at a point 110° B.T.C. was measured from either the 10 lb or 20 lb card, and the specific volume of the cylinder gases at this point was computed by the equivalent cycle method. (See Appendix A)

For the second run of the series using the same fuel and engine RPM but with 14.7 psia exhaust pressure and consequent lower residual gas content, it was necessary to duplicate this cylinder pressure and specific volume at 110° B.T.C.

To accomplish this, a new card was inserted in the indicator machine on which this same pressure was marked at 110° B.T.C. The inlet temperature was raised and the inlet pressure was adjusted until the compression line on the second run ran through the marked pressure point. With the pressure thus fixed, the remaining variable was the specific volume. This was computed by the same equivalent cycle method and, if

in disagreement with the volume found for the first run, the inlet temperature was lowered or raised to decrease or increase the specific volume. At the same time, the inlet pressure was readjusted to keep the compression line going through the marked point. After several trials, a combination of inlet temperature and inlet pressure was found to give the same pressure and volume in the cylinder at 110° B.T.C. as in the first run.

When this combination had been found, all variables were held constant and cards were again taken on the high-speed indicator machine.

This procedure was used for each fuel in an attempt to obtain identical compression entropies at 900 and 1800 RPM's. (See Precision of Results)

With Ethyl Benzene it was necessary to use an inlet temperature of 150° F instead of 120° F to insure complete vaporization of the fuel in the mixing tank. As a consequence, the volume for the high exhaust pressure run was so high that it could not be duplicated in the low pressure run by raising inlet temperature alone. Thus it was necessary to increase the exhaust pressure above the 14.7 psia value to raise the volume at 110° B.T.C. to the necessary value.

RESULTS

The results of this experiment are contained in Table I and Figures 5 and 6.

In all the fuels tested, the critical pressure increased with an increase in residual gas concentration, thus giving a positive slope to all plots of critical pressure versus residual gas concentration, regardless of RPM.

However, the difference in slope of the 1800 RPM line relative to the 900 RPM line for each fuel is caused by the change in the time of contact of the residual gas with the end gas. These differences in slope were found to be as follows:

Iso-Octane: The slope of the 900 RPM line is greater than that of the 1800 RPM line.

Ethyl Benzene: The slope of 900 RPM line is greater than that of the 1800 RPM line.

Triptane: The slope of the 1800 RPM line is greater than that of the 900 RPM line.

Di-iso-butylene: The slope of the 1800 RPM line is greater than that of the 900 RPM line.

With Iso-Octane a higher critical pressure was obtained with 1800 RPM regardless of residual gas concentration. However, Ethyl Benzene, Triptane and Di-iso-butylene gave higher critical pressures using 900 RPM for all values of residual gas concentration.

The pressure versus time curve (Fig. 6) shows that the rate of compression for 1800 RPM is greater than that for 900 RPM at all comparable points on the compression path.

DISCUSSION OF RESULTS

The results of this experiment (Fig. 5) show that there is a difference in the relative slopes of the 900 RPM and 1800 RPM lines for a given fuel.

Iso-Octane and Ethyl Benzene show the 900 RPM line as having a greater slope than the 1800 RPM line. This indicates that a shorter time of contact between the residual gas and the end gas allows the end gas to detonate more easily.

Di-iso-butylene and Triptane show the 1800 RPM line as having a greater slope than the 900 RPM line, giving opposite results to those obtained for Iso-Octane and Ethyl Benzene. That is, a shorter time of contact between the residual gas and the end gas allows the end gas to detonate less easily. The effects as evidenced by the slight differences in slope are quite small.

In an attempt to explain the above effects, it is assumed that residual gas in some way catalyzes or inhibits the preliminaries to detonation in the end gas. That is, if the chemical preliminaries to detonation were inhibited by the residual gas, as in the case of Iso-Octane and Ethyl Benzene, and if the preliminaries to detonation were catalyzed by residual gas as in the case of Di-iso-butylene and Triptane, then the observed effects are explained.

It must be pointed out that this discussion applies only

to the relative slopes of the 900 RPM and 1800 RPM lines for any given fuel and consequently deals only with the effect of residual gas concentration on the pressure-time characteristics of the fuels studied.

The results also show that all fuels at all RPM's have positive increases in critical pressure with an increase in residual gas concentration. This increase can be explained by the fact that the residual gas dilutes the end gas and may, therefore, inhibit the processes necessary to bring the end gas to explosion. This effect may be purely a physical one, i. e., keeping the reacting molecules of the end gas apart physically, thus reducing the rate at which chain reaction proceeds. The dilution effect is influenced by the participation of the residual gas components in the chemical preliminaries to detonation as discussed in the preceding paragraphs.

The rate of compression of the residual-end gas combination was higher at 1800 RPM than at 900 RPM, but under the experimental conditions used, there was no way of maintaining a constant rate of compression for all fuels at the same RPM. Hence, no comparative discussion can be made on the effect of rate of compression.

PRECISION OF RESULTS

DETONATION

The error involved in judging the detonation level of a given fuel under different operating conditions were almost entirely personal since the critical compression ratios were judged entirely by observation of the oscillograph pattern. A single operator was charged with the estimation of incipient detonation. The variation in compression ratio for several runs is given below for Triptane.

Run Number	Trial Number	Micrometer Reading	Compression Ratio	Error in Estimated C.R.
12	1	.204	7.39	0
12	2	.207	7.36	-.03
12	3	.202	7.41	+.02
12	4	.209	7.34	-.05

Other fuels were checked in a similar manner. It can be seen that the reproducibility of estimating the incipient detonation point was consistent within a maximum of plus or minus .05 units. It must be pointed out, however, that a different operator could easily get consistent results of higher or lower readings than those mentioned above. Since the oscillograph method is the best procedure yet found for detecting incipient detonation in the judgment of the authors, the fallibility of this method had to be accepted.

Appendix A: Notation

Notation

The notes involved in judging the discussion level of a given text under different grouping conditions were almost entirely personal since the critical comparisons twelve were largely certainly by chance of the multiple-group variance. A single observer was chosen with the estimates of inspired deficiencies. The returning in consideration ratio for several read by given below for clarity.

Item	Grade	Decimeter	Ratio	Deficiency
12	2	.694	7.89	0
12	2	.807	7.89	-.03
12	8	.888	7.63	+.02
12	4	.888	7.84	-.19

Other their were elected in a similar manner. It was to have that the significance of estimating the inspiring deficiencies point was accepted right a meeting of plus or minus .02 ratio. It does be impulse one, however, that a different observer would easily get consistent results at higher or lower readings than those mentioned above. Since the qualifying method is the best procedure yet found for determining inspiring deficiencies in the judgment of the matter, the feasibility of this method had to be accepted.

ENGINE INDICATOR

No error was assumed for the M.I.T. high-speed engine indicator card machine as the cyclic variation of cylinder pressures caused a line width and scatter of points greater than any inherent error in the machine.

Pressure measurement readings taken at 110° B.T.C. and 140° A.T.C. (for equivalent cycle computation) were accurate to the width of the compression and expansion lines at these points giving accuracy of within 1%. The measurement of peak pressures was more difficult due to considerable cyclic variation during the combustion process causing a spread of as much as 5% in peak pressure points. The actual average could be plus or minus 2% from the average measured.

The balanced pressure pick-up unit used was tested and the actuating pressure difference required was found to be .37 lb/in.^{2} Assuming the unit acted the same under operating conditions, this would be a 1.5 - 2.0% error at 110° B.T.C. and negligble error at all other pressures measured.

CLEARANCE VOLUME

The clearance volume of the engine was carefully measured by checking the measured clearance volume against figures obtained by Professor W. Leary, of the actual compression ratios required for definite cylinder volumes. The piston was set on top-dead-center, both valves closed

and distilled water was poured into the clearance volume until the volume was filled. The volume of water used was checked against the figures mentioned above. Reproducibility was found to be within 2%. It is estimated that less than 1% error in clearance volume versus compression ratio existed during the experiment.

AIR MEASUREMENT

Mass rate of air flow was calculated by the expression $M_a = .1825 (hP_o/T_o)^{\frac{1}{2}}$ where M_a = lb. air/sec., h = pressure drop across the orifice in inches of water, P_o = pressure before the orifice in inches of mercury and T_o = temperature of air before the orifice in ^oF abs.

Air flow was one of the most difficult of the variables to measure due to a periodic surge in the pressure drop across the orifice. A surge occurred when the main air supply compressor turned on causing a small increase in P_o and a larger increase in pressure drop across the orifice, despite two pressure regulator valves in series between the supply line and the engine induction system. Since the averaging of the value of pressure drop was done by the same operator for all runs, it is felt that the relative values of M_a are quite good, and, since the surges were on the order of 5%, the absolute error should not exceed 2%.

FUEL MEASUREMENT

The rotometer was calibrated by weighing each fuel with a sensitive balance. This calibration was done at various

fuel temperatures, the range being approximately 15°F. The curves could be read with a temperature accuracy of plus or minus 1° F. During running, however, the rotameter reading had an estimated variation of plus or minus 2%.

INLET TEMPERATURE

The inlet temperature was controlled within plus or minus 1°F of the desired reading.

RPM

The RPM could be controlled within a negligible error.

EXHAUST PRESSURE

The exhaust pressure was held within a plus or minus .5 psi when operating with high exhaust pressure. When low exhaust pressure was used, the variation was less than .1 inch of mercury.

REPRODUCIBILITY OF RESULTS

The criteria selected for the reproducibility of the apparatus were the pressure and specific volume at 110° B.T.C.

The recording run variables (i. e. inlet temperature, RPM, spark advance, coolant temperature, rotameter reading, exhaust pressure, inlet pressure) were duplicated correcting for fuel temperature. Incipient detonation was then, in the judgment of the oscillograph operator, reproduced. The reproducibility of critical experimental values is tabulated below for comparison.

	Compression Ratio	f	Critical Pressure	At 110° B.T.C. Vol.	Pressure
Triptane					
Recording run	7.80	.037	890	11.39	24.7
Check run	7.84	.037	890	11.30	24.7
Iso-Octane					
Recording run	8.76	.1025	723	14.4	20.9
Check run	8.67	.104	725	14.38	20.9
Di-iso-butylene					
Recording run	6.82	.051	705	12.97	21.5
Check run	6.77	.0518	708	12.8	21.5

A check run was not attempted on Ethyl Benzene due to lack of time.

It can be seen from the above data that the compression ratio variation at the maximum was 1%. The maximum variation

Reproducibility of Results

The critical molding for the reproducibility of the experiments using the pressure bar injection volume at 110° S.T.P.

The recording pen variables (i. e. input sensitivity, zero, chart advance, coarse vernier, fine vernier reading, column pressure, total pressure) were duplicated corresponding for test temperature. Duplicate determinations were taken, in the judgment of the analyst, satisfactory. The reproducibility of critical experimental values is tabulated below for comparison.

Material	Temperature Data	%	Critical Pressure	at 110° S.T.P. Tol.	Pressure
Decanoic Ether					
Recording run	7.80	.007	880	11.09	94.7
Check run	7.84	.007	890	11.10	94.7
Iso-Octane					
Recording run	6.76	.1459	720	10.4	91.9
Check run	6.87	.104	720	14.85	89.9
Di-iso-butylene					
Recording run	6.82	.080	708	12.87	91.7
Check run	6.77	.0812	708	12.5	91.9

A check run was not attempted on Decyl Decanoic Ether be cause of time.

It can be seen from the above data that the temperature ratio varied by the maximum was 1%. The maximum variation

in residual gas concentration was about 2%. Critical pressure and the specific volume and pressure at 110° B.T.C. were matched with negligible error. It is, therefore, estimated that the overall reproducibility of the apparatus was within plus or minus 1%.

SUGGESTIONS FOR FUTURE STUDY

Since the effect of residual gas concentration on the pressure-time characteristics of the fuels studied was not found to be the cause of the observed RPM-detonation reversal, it is suggested:

1. A similar experiment be conducted with no residual gas per cycle to see if the reversal effect is still present.

2. The straight line variation of critical pressure with residual gas concentration, as was assumed, should be investigated.

3. The effect of radiation from the flame front to the end gas should be studied.

4. The effect of inhibiting reactions (if any) in the early part of the compression process should be further investigated.

APPENDIX A

THE EQUIVALENT CYCLE METHOD

Symbols:

B = lbs. of air used per cycle

f = ratio of mass of residual gas to total gas mass per cycle

F = ratio of mass of fuel to mass of air per cycle

M = total gas mass

V = total gas volume

Derivation

In the cylinder:

The mass of fuel and air used per cycle = $B(1 + F)$ lbs.

Then the total gas mass per cycle = $\frac{B(1 + F)}{(1 - f)}$ lbs.

In the Hershey, Eberhardt, and Hottel charts of the thermodynamic characteristics of fuel-air mixtures before and after combustion:

The total chart mass = $(1 + F)$ lbs.

Therefore $\frac{V_{chart}}{V_{cyl}} = \frac{M_{chart}}{M_{cyl}} = \frac{(1 + F)}{B(1 + F)/(1 - f)}$

$= \frac{(1 - f)}{B}$

And thus, $V_{chart} = V_{cyl} \frac{(1 - f)}{B}$

$$= \frac{\pi}{(1 - x)}$$

$$\text{Derivative } \frac{d(\tan^{-1} x)}{dx} = \frac{\sec^2 y}{\frac{dx}{dy}} = \frac{(1 + x)(1 - x)}{(1 + x)}$$

The chief right hand = (1 + P) Ipe.

And other conditions:

Simultaneous characteristics of long-air missions having

In the Interest, Investment, and Credit Charge of the

Then the total ton miles Duc Right = $\frac{(x - 1)}{y(1 + x)}$ Ipe.

The sense of that car ore used for claim = 3(1 + P) Ipe.

In the Critique:

Distribution

I = Total Two Lanes

D = total Dua Rate

R = ratio of mass of fuel to mass of air Bar Right

C = ratio of mass of Equipment Dua to Total Gas mass Bar Claim

X = Ipe. of air-mass Bar Claim

Appeal:

SAMPLE CALCULATION FOR
ISO-OCTANE AT 900 RPM
(RUNS NO. 13 and 14)

Given: P_i = 31.68" Hg M_a = .00874 lb/sec.

T_i = 120° F F = 117.6% chem. correct

P_e = 45 psia M_f = .000675 lb/sec.

r = 8.72

Required to find (f):

$V_{clearance}$ = .002798 ft.^{3}

$V_{displaced}$ = .01958 ft.^{3} at 140° A.T.C.

$V_{cylinder}$ = .022378 ft.^{3}

$B = \frac{.00874 \times 2 \times 60}{900}$ = .001164 lb/air cycle

Now for first approximation assume f = .102

Then $V_{chart} = .022378 \times \frac{(1 - .102)}{.001164}$ = 17.23 ft.^{3}/lb.

At 140° A.T.C. P = 56.95 psia from indicator card

Now locating this point on the "burned" thermodynamic charts and expanding isentropically to an exhaust pressure of 45 psia, a corresponding volume was read which was 20.8 ft.^{3}/lb.

$V_{chart} = .002798 \times \frac{(1 - .102)}{.001164}$ = 2.155 ft.^{3}/lb. at top center

And, therefore, $f = \frac{2.155}{20.8}$ = .1036

Required to find thermodynamic conditions at 110° B.T.C.:

$V_{clearance}$ = .002798

$V_{displaced}$ = .01557 at 110° B.T.C.

$V_{cylinder}$ = .018368 ft.^{3}

$V_{chart} = .018368x\frac{(1 - .1036)}{.001164} = 14.12$ at 110° B.T.C.

From indicator card P = 20.85 psia

In the second run, exhaust pressure was lowered to 14.7 psia. To obtain similar thermodynamic conditions at 110° B.T.C., it was necessary to use:

$P_i = 32.66"Hg$

$T_i = 224° F$

$M_a = .009625$ lb/sec.

$M_f = .000751$ lb/sec.

This resulted in a critical compression ratio of 6.93.

$V_{clearance} = .003643$ ft.^{3}

$V_{displaced} = .01958$ ft.^{3} at 140° A.T.C.

$V_{cylinder} = .023223$ ft.^{3}

$B = \frac{.009625x2x60}{900} = .001282$ lb/air cycle

For first approximation assume f = .05

Then $V_{chart} = .02322x\frac{(1 - .05)}{.001282} = 17.2$ ft.^{3}/lb. at 140° A.T.C.

From indicator card P = 59.45 psia

Again expanding isentropically from this point on the "burned" chart but to an exhaust pressure of 14.7 psia, the corresponding volume was 51.0 ft.^{3}/lb.

$V_{chart} = .003644x\frac{(1 - .05)}{.001282} = 2.70$ ft.^{3}/lb. at top center

And $f = \frac{2.70}{51.0} = .0529$

$T_{quench} = .0[illegible]\left(\frac{[illegible]}{.0[illegible]}\right) = 14.1R$ at 110^{0} B.T.U.

Thus Intercooler Load 3 = 17.8% Gain

In the second Two, exhaust pressure was lowered to 14.7 psia.

Or within similar thermodynamic conditions at 110^{0} B.T.U.,

It was necessary to have:

$P_1' = 20.81^{+}$

$T_1' = 540_{0}$ +

$P_2' = .0[illegible]$ lb/sec.

$W_2' = .0[illegible]$ lb/sec.

This resulted in a critical compression ratio of 6.32.

$T_{discharge} = .[illegible]$ P_2'

$T_{difference} = .0[illegible]$ P_2' at 120^{0} F.T.C.

$T_{cylinder} = .0[illegible]$ P_2'

$\gamma = \frac{[illegible]}{[illegible]} = .0[illegible]$ lbs/lbs cycle

For first approximation assume $\gamma = .0[illegible]$

Then $T_{check} = .0[illegible]\left(\frac{\gamma - .0[illegible]}{.0[illegible]}\right) = 17.1$ P_2'/lb. at 140^{0} F.T.C.

Thus Intercooler Load 2 = 21.8% Gain

Again approximate theoretical flow into this point on the

"second" cooler, but to be closely proximate of 14.7 psia.

Use corresponding values when $P_2' = 13.8$ lb/in.

$T_{check} = .0[illegible]\left(\frac{[illegible]}{.0[illegible]}\right) = 3.50$ lb.^{3}/in. at top cooler

And $\gamma = \frac{0.72}{21.0} = .0[illegible]$

To find the thermodynamic conditions at 110° B. T. C.:

$V_{clearance} = .0036437 \text{ ft.}^3$

$V_{displaced} = .01557 \text{ ft.}^3$

$V_{cylinder} = .019213 \text{ ft.}^3$

$V_{chart} = .019213 \frac{(1 - .0529)}{.001282} = 14.21 \text{ ft.}^3/\text{lb. at } 110^\circ \text{ B.T.C.}$

From indicator card P = 20.85 psia.

The points thus found for 110° B.T.C. were indistinguishable from each other when plotted on the "unburned" chart, and, therefore, were considered to be identical in entropy.

To find the corresponding conditions at 120° S. I. C.:

$$A_{\text{Cleavage}} = .0000247 \text{ in.}^2$$

$$A_{\text{Applied}} = .0125 \text{ in.}^2$$

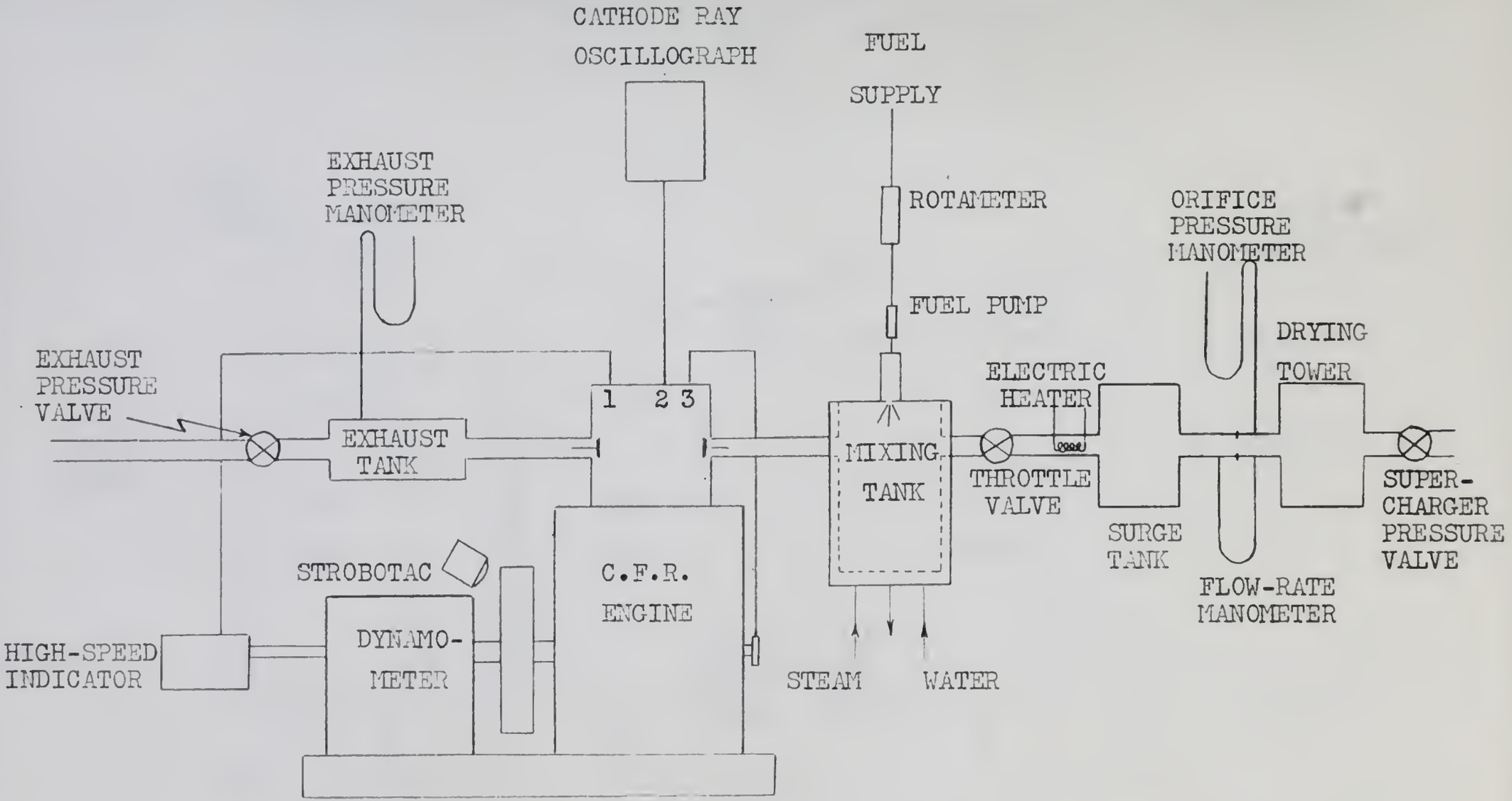
$$A_{\text{Cylinder}} = .01275 \text{ in.}^2$$

$$A_{\text{Piston}} = .01227 \left(\frac{.0125}{.01275}\right) = 15.91 \text{ in.}^2 \text{ at } 120^\circ \text{ S.I.C.}$$

Dome Resistance Load = 84.69 pulls.

The points thus found for 120° S.I.C. were interpolated
from each other plotted on the "corrected" curve, and,
therefore, were considered to be plotted to accuracy.

APPENDIX B



1. INDICATOR PICKUP
2. RATE OF PRESSURE PICKUP
3. SPARK PLUG

FIGURE 1

OVERALL LAY-OUT
of
EXPERIMENTAL C.F.R.
SET-UP

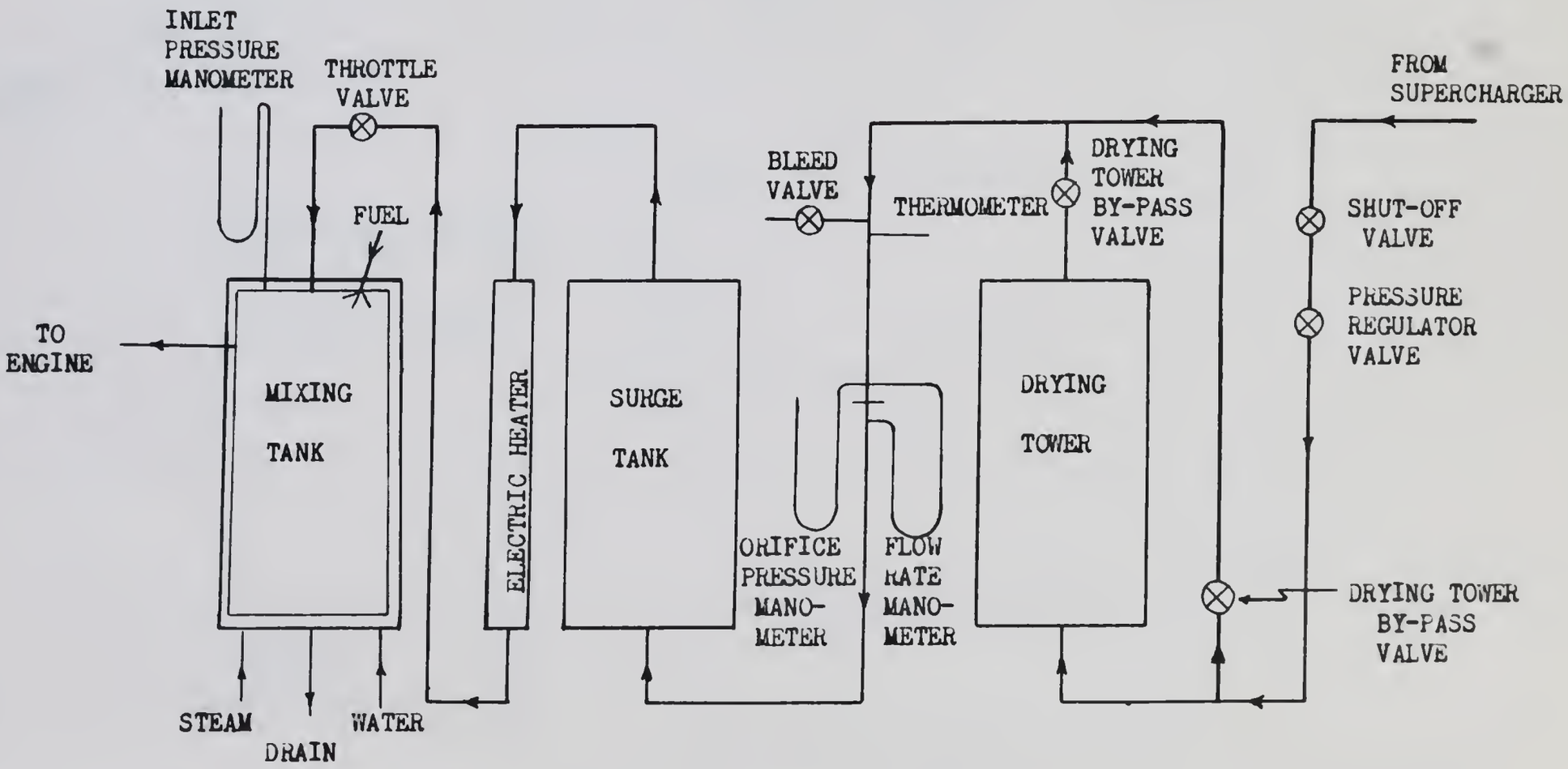


FIGURE 2
DETAILED LAY-OUT
of
INDUCTION SYSTEM

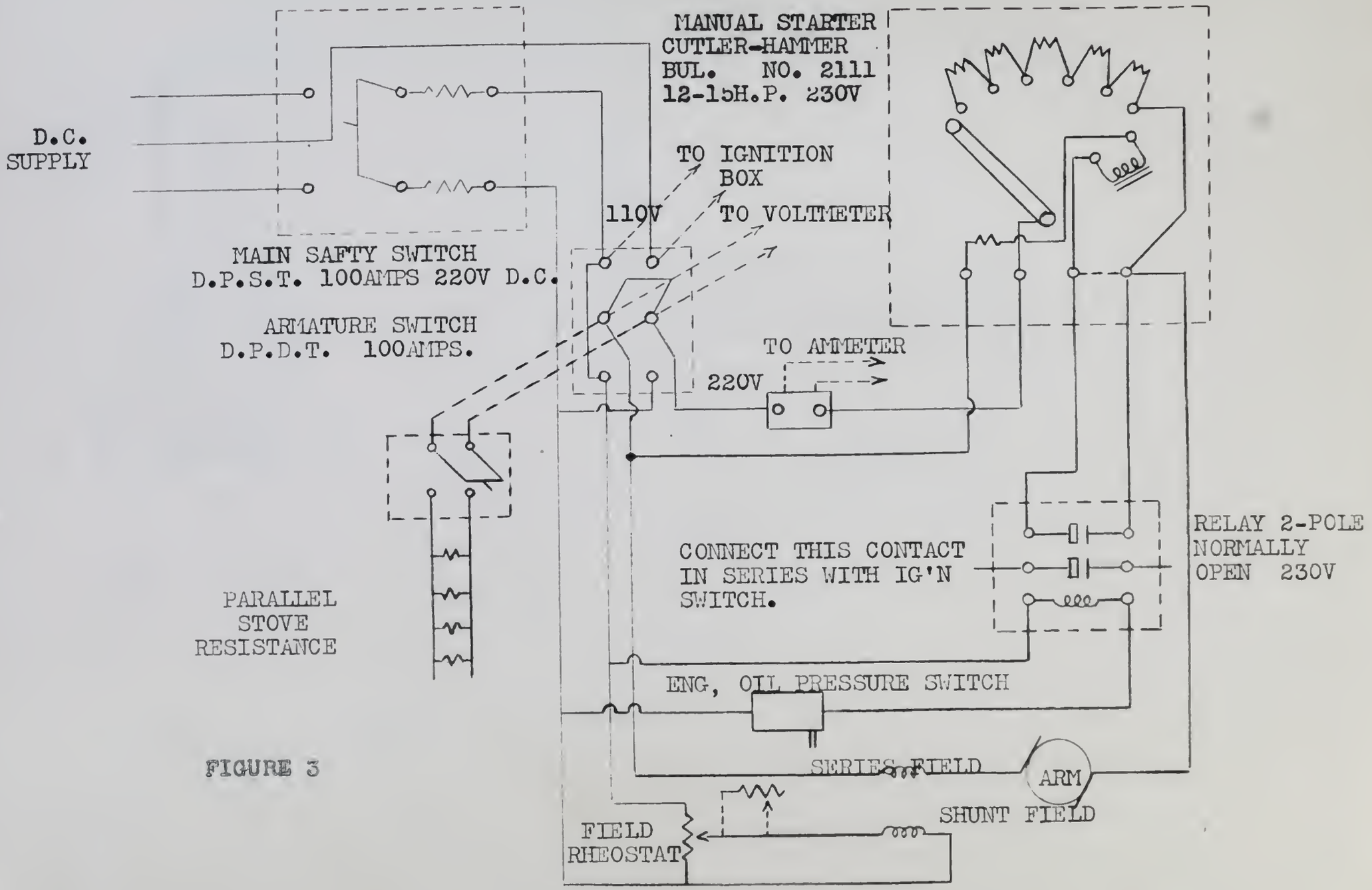


FIGURE 3

WIRING DIAGRAM OF STAR DYNAMOMETER C.F.R. ENGINE SETUP

HIGH SPEED INDICATOR

M. I. T.

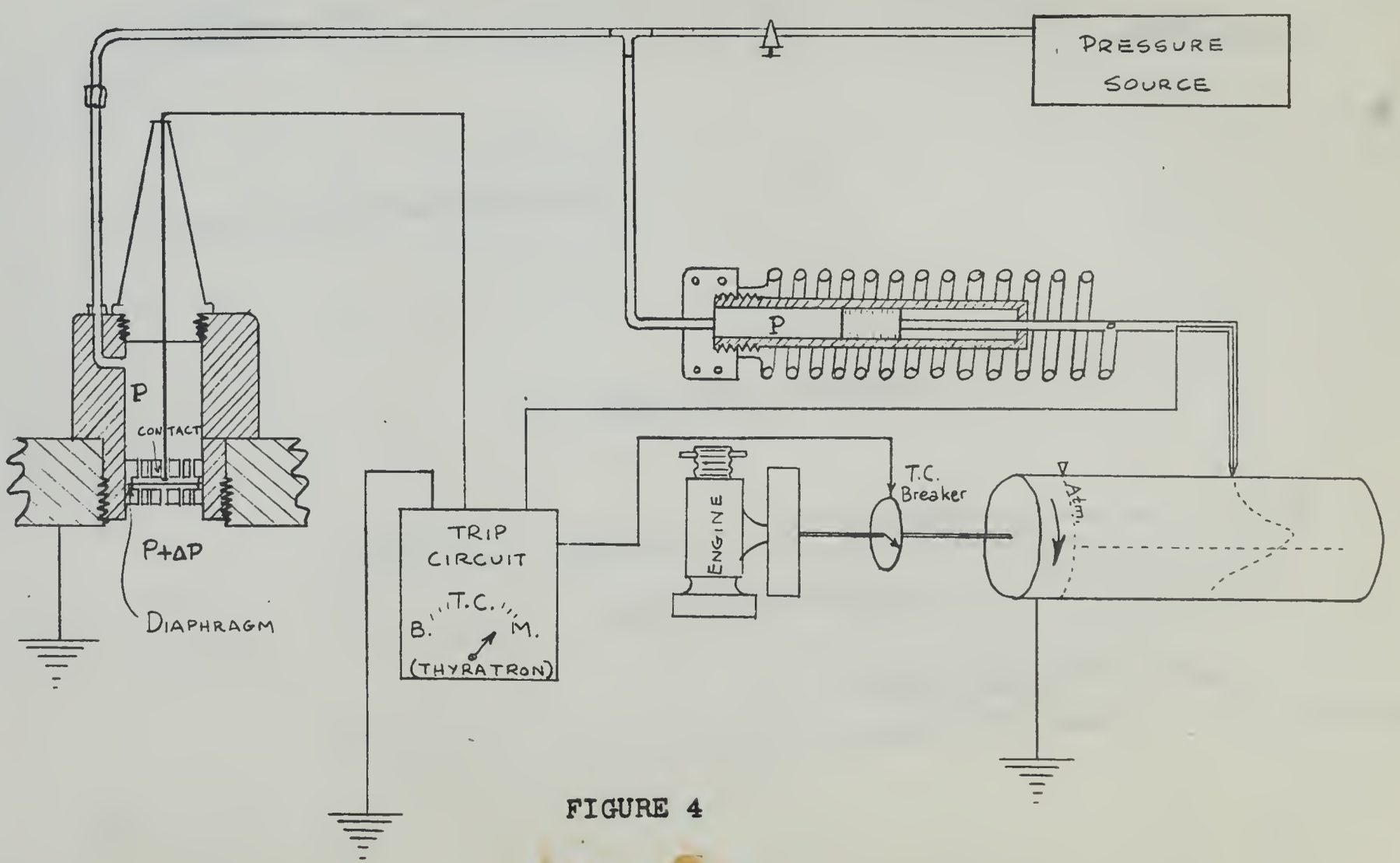
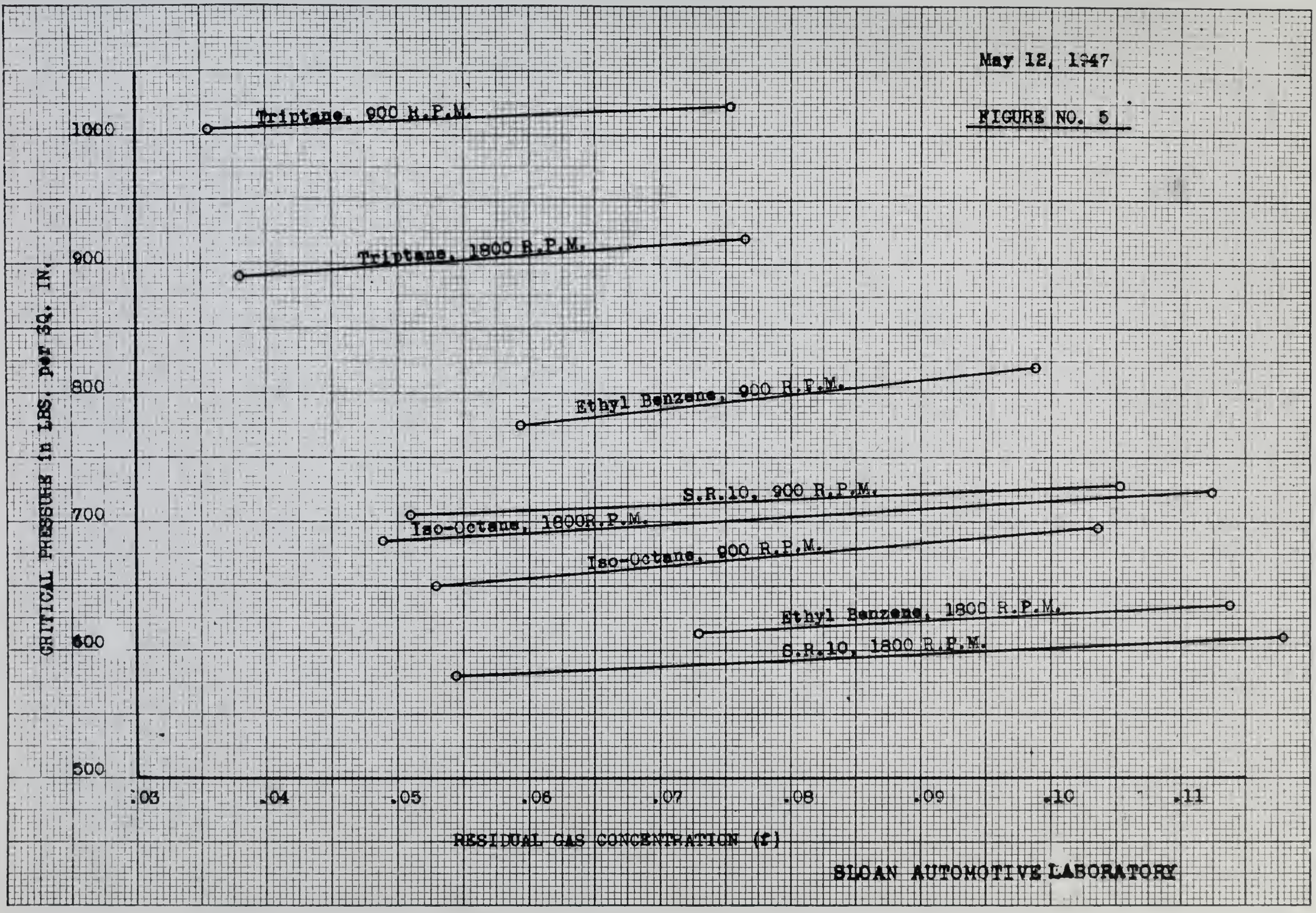


FIGURE 4

11/23/39 J.G.

May 12, 1947

FIGURE NO. 5



SLOAN AUTOMOTIVE LABORATORY

PLOTS OF
CYLINDER PRESSURE
vs.
TIME
FOR ISO-OCTANE

Sloan Laboratory
May 13, 1947

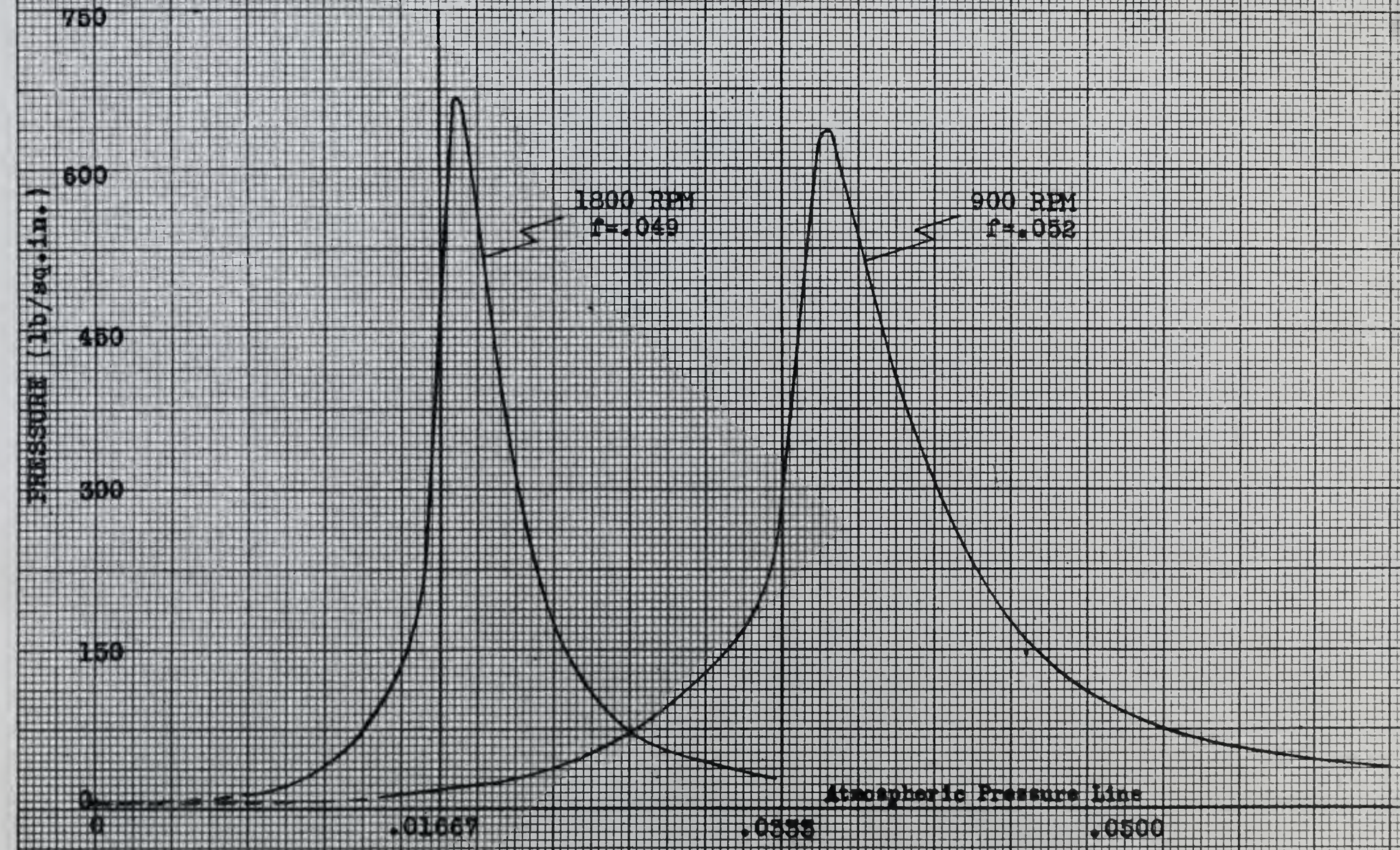


Fig. 6

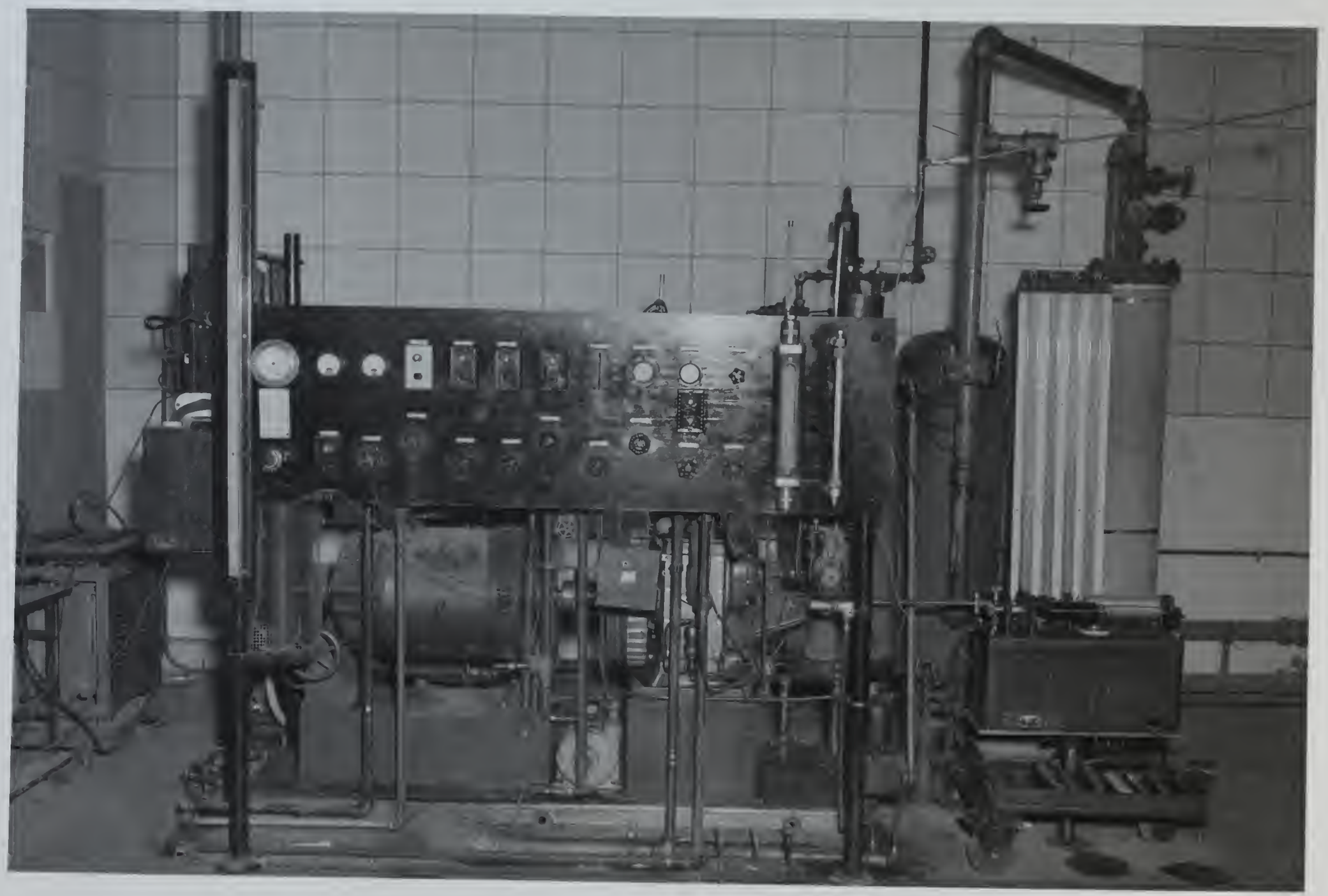
M.I.T. AERO ENGINE LABORATORY

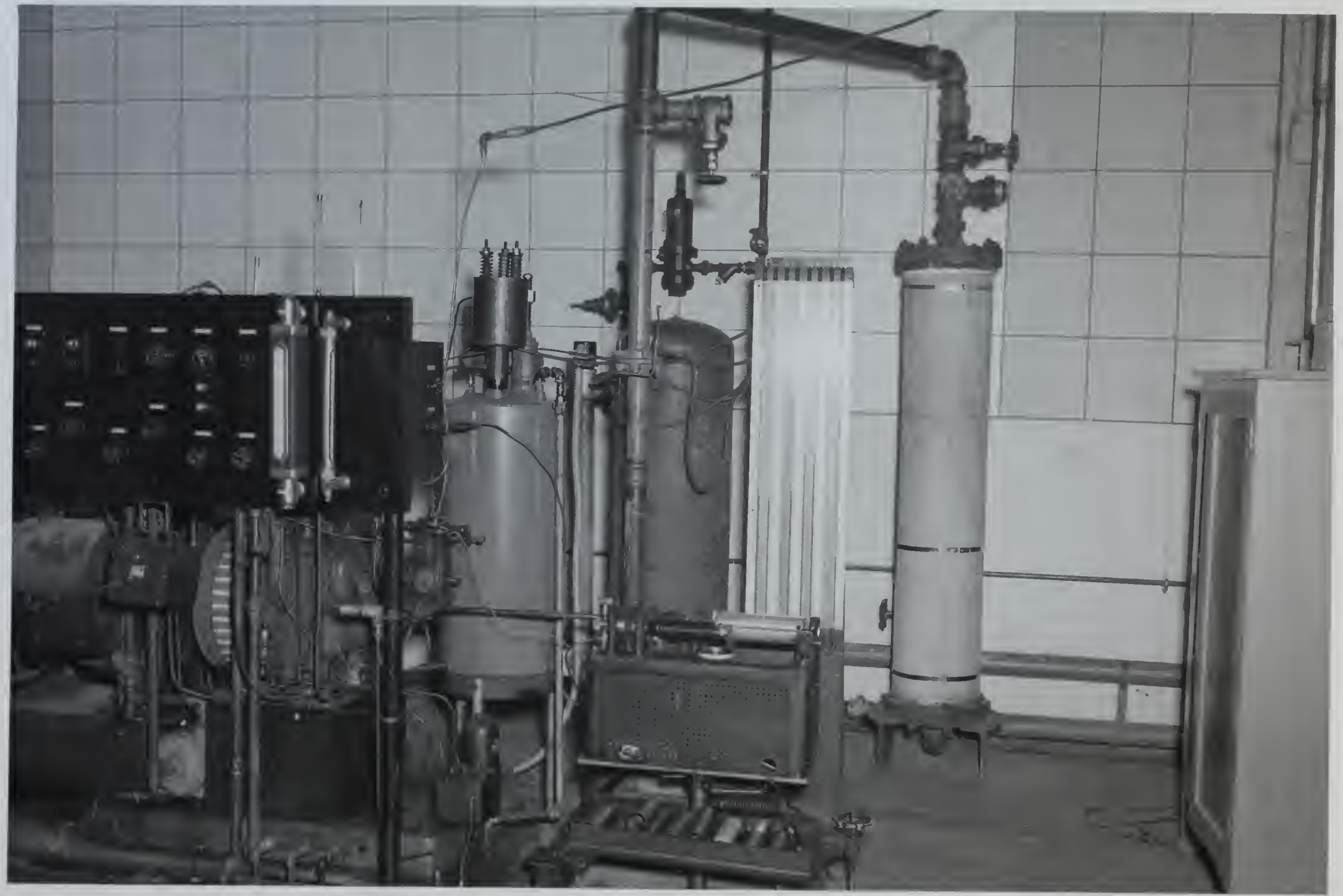
CFR ENGINE — 3.25 BORE 4.5 STROKE — Variable COMPRESSION RATIO

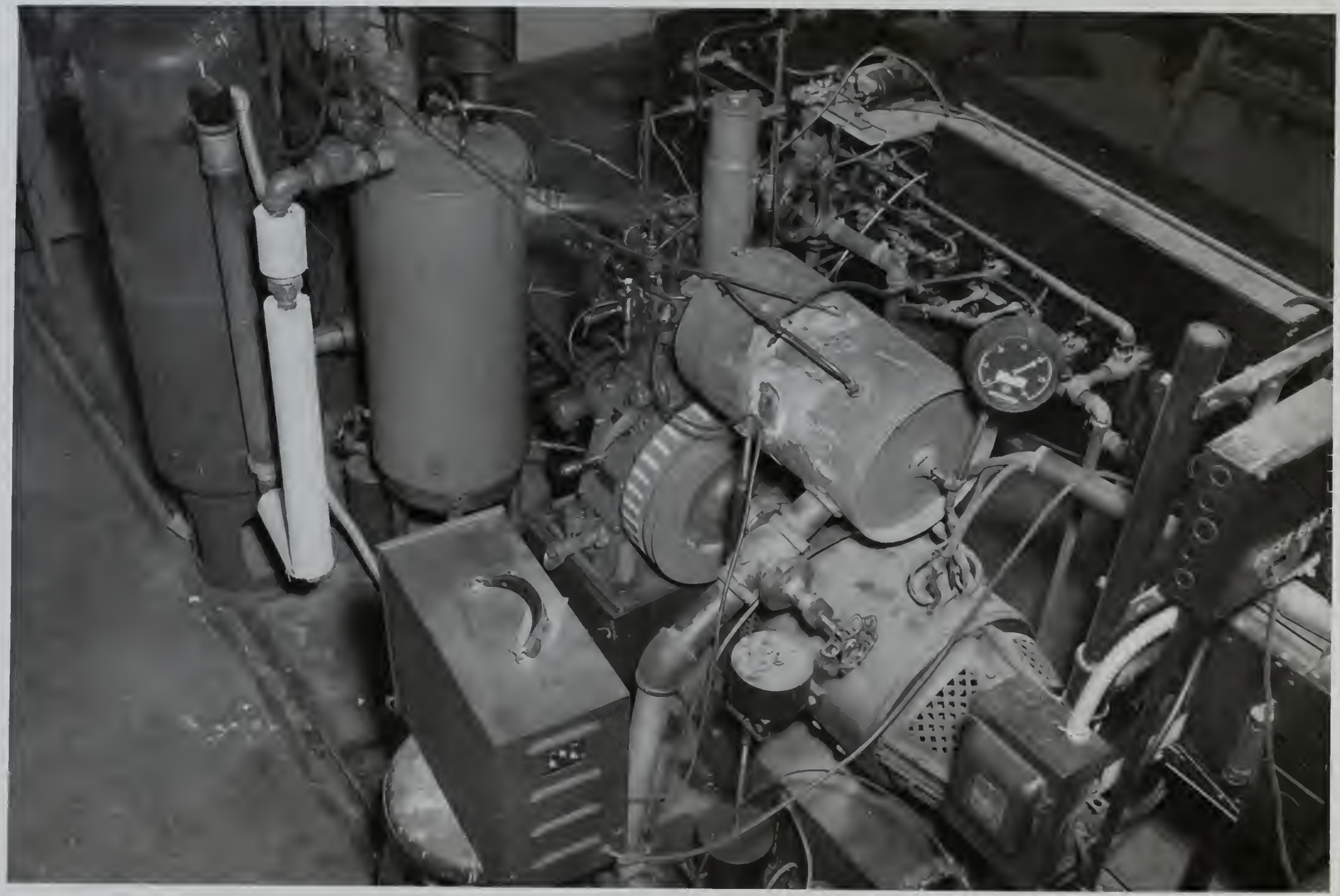
REMARKS	DATE	TIME	Run	P_a "Hg	P_e Psia	P_i "Hg	P_o "Hg	T_o °F	T_i °F	T_f °F	M_a lb/sec	F	$M_f \cdot 10^6$ lb/sec	Ratio	r_{min}	r	SA °BTC	N RPM	P_{exh} Psia	f	V ft³/lb	P Psia
TRIPTANE	4-17		1	29.79	45	43.99	44.41	91	120	87	.01307	.07785	1018	8.8	.066	8.95	15	900	1023	.0755	9.7	28.0
	4-17		2	30.08	14.7	43.98	44.48	100	160	88	.01397	.07785	1086	9.15	.172	7.70	15	900	1005	.036	9.73	28.0
	4-18		3	29.91	45	40.21	42.26	82	120	84	.0222	.07785	173	12.93	.098	9.21	20	1800	920	.077	11.35	29.79
	4-18		4	29.83	14.7	40.93	43.41	100	200	88	.0238	.07785	1852	13.52	.142	7.80	20	1800	890	.037	11.34	29.1
Check of run #4	4-18		5	29.80	14.7	40.93	43.41	100	200	88	.0238	.07785	1852	13.52	.158	7.84	20	1800	895	.037	11.3	29.7
ETHYL BENZENE	4-29		6	30.20	45	33.45	34.47	80	150	87	.00935	.0865	0808	8.02	.098	8.53	20	900	820	.0888	13.33	22.78
	4-29		7	30.20	20.15	34.8	35.5	89	222	93	.00986	.0865	0859	8.3	.140	8.01	20	900	775	.0549	13.33	22.75
	5-1		8	29.95	45	32.7	34.2	80	150	85	.01652	.0865	1428	11.72	.179	7.63	25	1800	635	.1138	15.15	21.4
	5-1		9	29.95	22.4	33.15	35.1	94	235	90	.0178	.0865	1540	12.35	.266	6.87	25	1800	613	.0729	15.09	21.4
ISO-OCTANE	4-24		10	29.95	45	32.39	33.35	76	120	85	.01713	.0782	1340	10.22	.080	8.76	25	1800	723	.1025	14.9	20.9
Check of run #10	4-24		11	30.46	45	32.34	33.94	86	120	86	.0172	.0782	1340	10.2	.087	8.67	25	1800	725	.109	14.38	20.9
	4-24		12	29.95	14.7	33.50	35.60	95	249	94	.0185	.0782	1450	11.00	.209	7.39	25	1800	685	.0989	14.59	20.9
	4-24		13	29.81	14.7	32.66	33.36	98	229	90	.00963	.0782	0751	7.1	.259	6.93	20	900	650	.0529	19.21	20.85
	4-24		14	29.81	45	31.68	32.06	98	120	90	.00874	.0782	0675	6.85	.083	8.12	20	900	695	.1036	19.12	20.85
SR-10	4-15		15	29.95	45	30.65	32.05	92	120	90	.0160	.08	1280	9.98	.140	8.03	25	1800	610	.118	15.90	19.0
	4-15		16	29.95	14.7	31.85	33.80	103	210	93	.01788	.08	1430	10.7	.312	6.59	25	1800	580	.0595	15.94	19.0
	4-15		17	30.00	45	33.15	34.35	80	120	88	.00967	.08	0773	7.3	.140	8.03	20	900	730	.1053	13.09	21.5
	4-15		18	30.00	14.7	34.4	35.15	86	195	91	.0106	.08	.0848	7.6	.273	6.82	20	900	705	.051	12.97	21.5
Check of run #18	4-15		19	30.00	14.7	34.4	35.15	79	195	83	.0109	.08	0870	7.6	.280	6.77	20	900	700	.0518	12.8	21.5

SYMBOLS:

P_a	Atmospheric Pressure	T_o	Temperature of air before measuring orifice.	V	Specific volume of cylinder gases at 110° B.T.C.
P_e	Exhaust Pressure	T_i	Inlet temperature of fuel-air mixture entering engine intake port.	P	Absolute pressure of cylinder gases at 110° B.T.C.
P_i	Inlet Pressure or total pressure of fuel-air mixture in the vaporizing tank.	T_f	Temperature of fuel leaving rotameter.	r	Compression ratio.
P_o	Pressure of air before measuring orifice.				







APPENDIX C

APPENDIX C

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(1) Leary, W. A., and Taylor, E. S., The Significance of the Time Concept in Engine Detonation, N.A.C.A. ARR, January 1943.

(2) Taylor, E. S., and Draper, C. S., "A New High Speed Engine Indicator", Mechanical Engineering, Vol. 55, No. 3, 1933, p. 169.

(3) Draper, C. S., "Pressure Waves Accompanying Detonation in the Internal Combustion Engine", JAS, Vol. 5, No. 6, April 1938.

(4) Taylor, E. S., Leary, W. A., and Diver, J. R., Effect of Fuel-Air Ratio, Inlet Temperature, and Exhaust Pressure on Detonation, N.A.C.A. Report No. 699.

DATE DUE			

Thesis 3093
S666 Sorensen

The effect of residual gas concentration and engine speed on the detonation characteristics of iso-octane, di-isobutylene, triptane, and ethyl benzene.